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CTOD toughness correction for laser welded joints with narrow hardened zone

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Abstract

The influences of very narrow weld bead and highly strength overmatching on the fracture toughness of laser beam welded components are investigated. This study focuses on the difference of plastic constraint in fracture toughness specimen (3-point bend specimen, 3PB) and structural components with crack in the weld metal. The equivalent crack tip opening displacement (CTOD) ratio, β, for the correction of CTOD toughness for constraint loss in structural components is numerically analyzed. The narrowness of weld bead induces constraint loss by plastic deformation in the base metal, both the 3PB and structural components. Nevertheless, in the case of the wide plate with shallow crack, the highly strength overmatching elevates the opening stress. Therefore, it is found that the β increase with increasing strength mismatch ratio. The influence of highly strength overmatching on β is important for assessment of fracture performance of laser beam welded component. The applicability of β to correction of critical CTOD in laser beam welded components is discussed. The fracture toughness tests with the 3PB and tension panel (edge through-crack panel) of the laser beam welded joints were conducted at a low temperature in the brittle fracture range. It is indicated that β can be applied to the CTOD toughness correction in laser beam welded component.

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Keywords: CTOD fracture toughness; constraint loss; laser welded joints; weld strength mismatch; Weibull stress

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1. Introduction

Laser beam welding has benefits in terms of deep penetration and high welding speed with significantly less weld distortion than the conventional arc welding. Single pass welding in 12 mm thickness is now possible using a standard I-butt joint (Kristensen, 2009). High energy density leads to fast cooling rate, which induces extremely hardened microstructure in weld metal (WM) and heat affected zone (HAZ). Thus, laser welded joints have highly strength overmatching between WM and base metal (BM).

In this study, the influences of very narrow weld bead and highly strength overmatching on the fracture toughness of laser beam welded components are investigated. The equivalent crack tip opening displacement (CTOD) ratio, β, for the correction of CTOD toughness for constraint loss in structural components is numerically analyzed. The applicability of β to correction of critical CTOD in laser beam welded components is discussed.

2. FE-analysis of stress fields for laser welded joints

The crack tip stress fields for laser beam welded joints were numerically analyzed with a three-dimensional finite element code [Abaqus standard Ver-6.12]. Figure 1 shows the wide plate models and 3PB specimen employed in FE-analysis. The plate thickness t of the wide plate models was 12 mm, which was equal to the thickness B of the 3PB specimen. The width and length of the wide plate models were 400 mm and 800 mm, respectively. CSCP had a surface crack of length $2c$ = 40 mm and depth a = 3 mm, which corresponds to the same size of the equivalent through-thickness crack, $2\bar{a}$ = 8.7 mm, in terms of the stress intensity factor K. ETCP had double edge through-thickness crack of depth $2a$ = 7 mm, which corresponds to the equivalent through-thickness crack of $2\bar{a}$ = 8.7 mm. The 3PB specimen was of the standard type (a/W = 0.5, W = $2B$). The crack was located in center of WM.

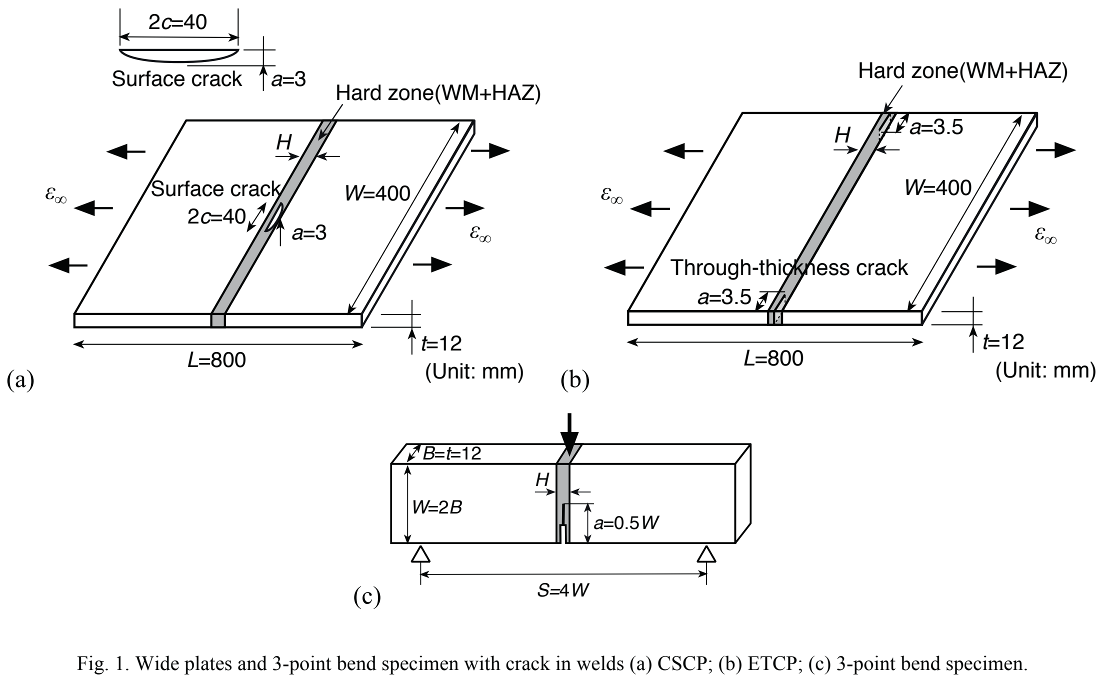


Fig. 1. Wide plates and 3-point bend specimen with crack in welds (a) CSCP; (b) ETCP; (c) 3-point bend specimen.

The CTOD of the surface crack was defined at the deepest point of the crack by a tangential method (Harrison, 1980). The CTODs of the 3PB specimen and the wide plate with a through-thickness crack were calculated from the load and mouth displacement V_g, according to BS 7448 Part2 (BSI, 1997) and by the Dugdale model (Bilby et al., 1964), respectively.

Table 1 lists the mechanical properties of the BM, HAZ and WM used in the FE-analysis. 780 MPa strength class steel with YR = 0.90 was assigned as the BM. The WM strength was varied in the range 1.2 ≤ Sr ≤ 2.0, where Sr is the strength mismatch ratio defined as $\sigma_T^{WM}/\sigma_T^{BM}$. The HAZ strength was set to the same strength as the WM. The stress – strain relations of the materials followed the power-hardening law of Swift type

$$\bar{\sigma} = C\left(1+\bar{\varepsilon}_{\mathrm{p}}/\alpha\right)^{n} \tag{1}$$

where $\bar{\sigma}$ and $\bar{\varepsilon}_{\mathrm{p}}$ are the equivalent stress and equivalent plastic strain, respectively, C is the elastic limit (yield stress), and n and α are material constants (n being a strain-hardening coefficient). The σ_Y is given in Table 1 is the nominal stress at 0.2% plastic strain derived from Eq. (1).

In this study, the hard zone consisted of WM and HAZ and the hard zone width H was 4 mm.

The FE-analysis used the eight-node element with eight Gaussian integration points; and the minimum element size at the crack tip was dimensions of 0.03 × 0.03 × 0.2 mm.

Table 1. Mechanical properties of base metal, HAZ and weld metal used for FE-analysis.

	Yield stress σ_Y (MPa)	Tensile strength σ_T (MPa)	Uniform elongation ε_T (%)	YR=σ_Y/σ_T	Sr=$\sigma_T^{WM}/\sigma_T^{BM}$	$\sigma_Y^{WM}/\sigma_Y^{BM}$
BM	702	780	10.3	0.90	—	
WM & HAZ	778	936	10.1	0.83	1.2	1.1
	900	1092	10.5	0.82	1.4	1.3
	1022	1248	10.9	0.82	1.6	1.5
	1144	1404	11.1	0.82	1.8	1.6
	1267	1560	11.3	0.81	2.0	1.8

3. Toughness correction method

In this study, the Weibull stress σ_W is used as a driving force for brittle fracture. The Weibull stress (Beremin, 1983) is given by integrating a near-tip stress σ_{eff} over the fracture process zone V_{f} in the form

$$\sigma_{\mathrm{W}} = \left[\frac{1}{V_0}\int_{V_{\mathrm{f}}}\left(\sigma_{\mathrm{eff}}\right)^{m} dV_{\mathrm{f}}\right]^{1/m} \tag{2}$$

where V_0 and m are the reference volume and a material constant, respectively, Vf almost corresponds to the plastic

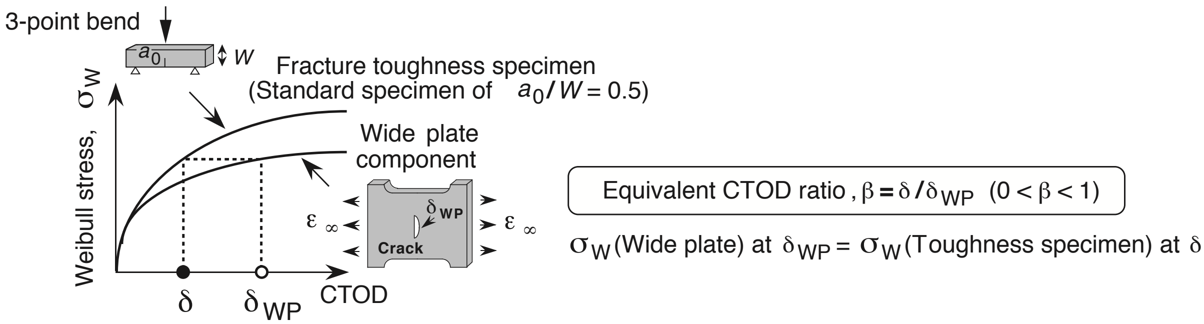


Fig. 2. Equivalent CTOD concept for link between fracture toughness specimen and wide plate component at same Weibull stress level.

zone near the crack-tip and σ_{eff} is an effective stress for cleavage fracture that is normally represented by the maximum principal stress. An effective stress (Minami et al., 1990; Ruggieri et al., 1992) considering a random spatial distribution of microcracks was employed as σ_{eff} in Eq. (2). The selection of V_0 does not affect the transferability analysis among different specimen geometries, and the shape parameter m-value has no relation with V_0. Hence, a unit volume of 1 mm^3 is often used as V_0 for convenience (Minami et al., 1992). This analysis also adopted V_0 =1 mm^3. The V_f for the specimen with a crack in the WM was defined in the WM, assuming that the WM controls the initiation of brittle fracture.

For CTOD toughness the correction for constraint loss, the equivalent CTOD ratio, β, was proposed (Minami et al., 1999) (Fig. 2):

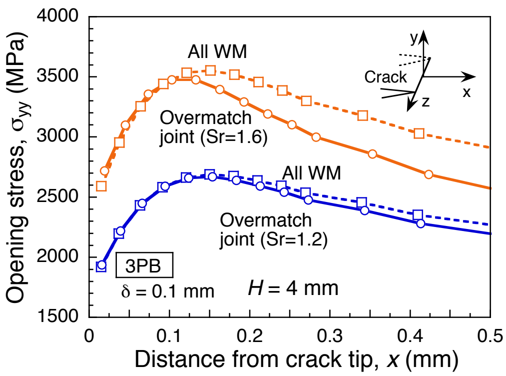
$$\beta = \delta / \delta_{WP} \tag{3}$$

where δ and δ_{WP} are CTODs of the standard fracture toughness specimen of a/W=0.5 and the wide plate, respectively, at the same level of the Weibull stress. The equivalent CTOD ratio, β, is in the range $0 < \beta < 1$.

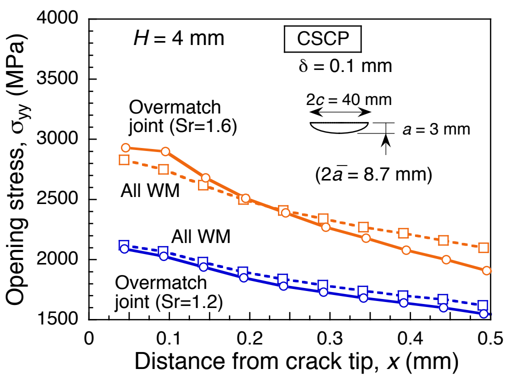
In this study, the effect of strength overmatching in welds and hard zone width on β were investigated.

4. Narrow hard zone and highly strength overmatching effect on *β*

The influences of narrow hard zone and highly strength overmatching on the crack tip constraint are investigated. Figure 3 shows the distributions of opening stress ahead of crack tip for the 3PB specimen and the wide plate models at the same CTOD level of δ=0.1 mm. Stress distribution for strength overmatch joints are compared with that for homogeneous WM model (all WM) that consists of weld metal properties in strength.



(a)



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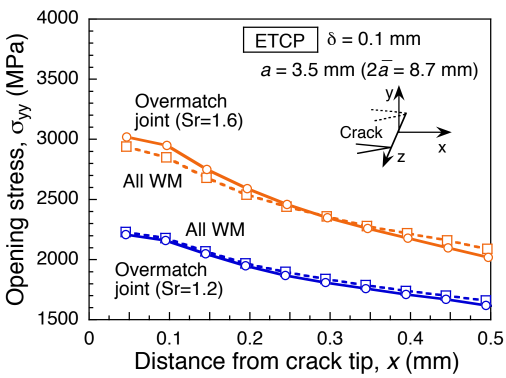

(c)

Fig. 3. Strength overmatching effect on crack opening stress distribution ahead of crack tip (a) 3PB; (b) CSCP; (c) ETCP.

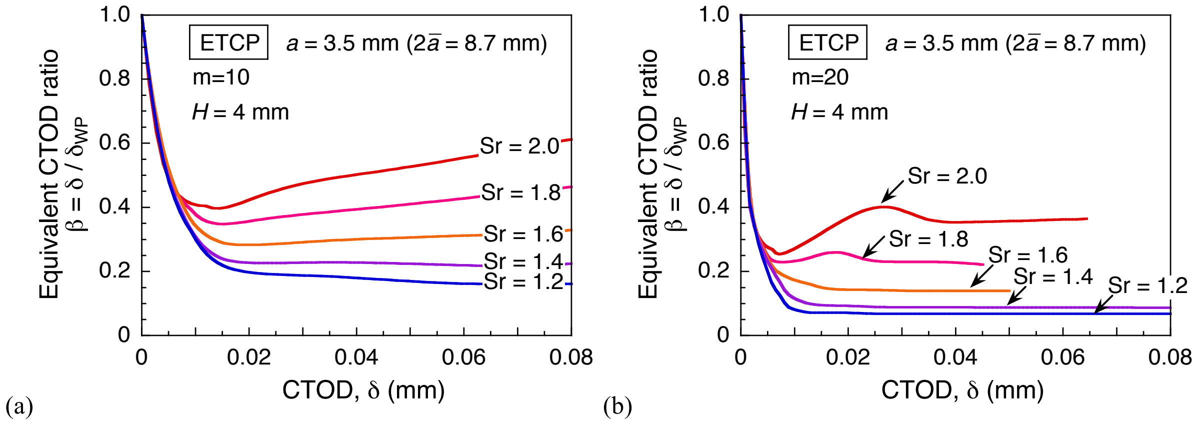

Fig. 4. Effect of strength mismatch on β for ETCP (a) m=10; (b) m=20.

Strength overmatching decreases the opening stress ahead of crack in WM for the 3PB specimen, because the narrowness of weld bead induces constraint loss by plastic deformation in the BM. The effect of strength overmatching on opening stress is more significant with increasing mismatch ratio, Sr. On the other hand, in the case of the wide plate models, the opening stress near crack tip for sufficient overmatching (Sr=1.6) is higher than that for homogeneous WM model, whereas the similar constraint loss to the 3PB specimen is appeared for mismatch ratio Sr=1.2. This will be due to general yielding preceded in the low-strength BM area. Consequently, the crack ligament in the WM is restrained from full yielding. Thus, the existence of the elastic area ahead of the crack tip acts like a constraint elevating the opening stress close to the crack tip.

Figure 4 shows the strength mismatch effect on β for the ETCP with crack in narrow welds (H=4 mm), respectively. It is found that β increase with increasing Sr for the ETCP. This is due to the plastic constraint caused by the existence of the elastic area ahead of the crack tip for wide plate models from full yielding in the low-strength BM area. For a low m-value, β is more sensitive to the strength mismatch. The increase in β by strength overmatching should be noticed for highly strength mismatched weldments.

5. Application of equivalent CTOD ratio to fracture toughness correction in laser welded structural component

The applicability of β to correction of critical CTOD in laser beam welded components is discussed. The steel of 780 MPa strength class with thickness t=12 mm was welded by single-pass CO_2 laser beam welding (laser power: 13.5 kW) with heat inputs of 60.6 kJ/mm (Takashima et al. 2009). The hardness of HAZ is approximately the same as that of WM, and the hard zone width H, which including WM and HAZ, is approximately 4 mm. The Vickers hardness ratio of WM to BM, Sr_{HV} (=HV_{WM}/HV_{BM}) is about 1.5.

Fracture tests with 3PB specimen and double edge cracked tension (DECT) semi-wide plate (width W=90 mm, crack depth 2a=30 mm) were conducted at –60 °C corresponding to the temperature at which brittle fracture occurred in the weld metal. The through-thickness crack was located in the center of WM. All DECT plates and 3PB specimens failed in a brittle manner. A distinct ductile crack growth prior to brittle fracture was not observed. The median critical CTOD of the 3PB specimens was 0.027 mm for 13 tests, where the CTOD value was determined in accordance with BS 7448 Part2 (BSI, 1997) with the WM yield stress.

The equivalent CTOD ratio, β, for the DECT semi-wide plate was calculated with FE-analysis. The Weibull parameter m=10 was selected, because the average critical CTOD<0.05 mm of 3PB specimen (Minami et al. 2006). The critical CTOD of DECT semi-wide plate, δ_{WPcr} was predicted from 3PB test results using β. Figure 5 shows the comparison between critical CTODs measured in the DECT test and predicted from 3PB test results using β. The prediction of critical CTODs agree well with experimental data. This result validates that β can be applied to the CTOD toughness correction in laser beam welded structural component.

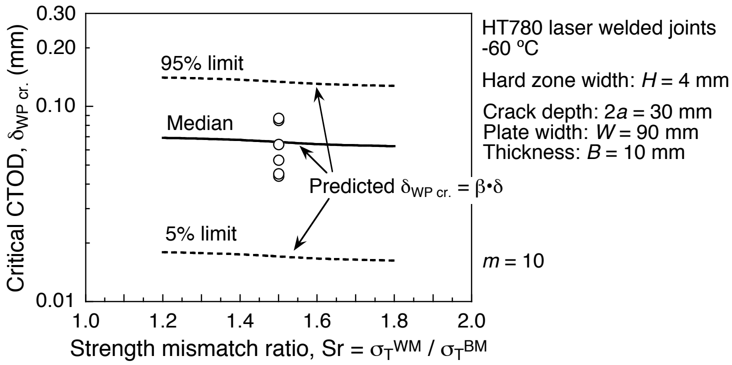

Fig. 5. Comparison between critical CTODs measured and predicted from using equivalent CTOD ratio, β.

6. Conclusions

This paper discussed the influences of very narrow weld bead and highly strength overmatching on the fracture toughness of laser beam welded components with focus on the difference of plastic constraint in fracture toughness specimen and structural components with crack in the weld metal. The equivalent CTOD ratio, β, for the correction of CTOD toughness for constraint loss in structural components was numerically analyzed.

With numerical results, high level of strength overmatching decreases the opening stress ahead of crack in narrow WM for the 3PB specimen. By contrast, the opening stress for wide plate with shallow crack in narrow WM is elevated by the high level of strength overmatching. Therefore, the β increase with increasing strength mismatch ratio. It was found that the highly strength overmatching is not beneficial to the effect of constraint loss in structural component. It was demonstrated that β can be applied to the CTOD toughness correction in laser beam welded structural component. The influence of narrow weld bead and highly strength overmatching on β is important for assessment of brittle fracture performance of laser beam welded component.

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